01 Jun 1993 - 06 Jun 1993

Analysis and Performance of Raft and Raft-Pile Systems

I. K. Lee
University of New South Wales, Canberra, Australia

Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, SOA 4

Analysis and Performance of Raft and Raft-Pile Systems

I. K. Lee
Professor of Civil & Maritime Engineering, University College, University of New South Wales, Canberra, Australia

SYNOPSIS A brief review is made of the development of the analyses of structure-raft and structure-raft-pile systems. Examples are presented to illustrate the scope of present-day analyses. The applicability of the linear analysis is examined by comparing predicted and measured values of settlements, contact pressure and pile loads. Consideration is given to the influence of the soil constitutive model on predicted values.

Introduction

Raft and raft-pile foundations form a complex structural system. An analysis aimed at predicting the settlements, pile loads and bending moments in the raft needs to take into account the characteristics of the structure, raft, pile and soil elements of the system.

One traditional approach to the analysis of a raft foundation was to reduce the analysis to a statical solution simply by imagining that the contact pressure distribution was linear. This approach may, if the designer chose, involve the structure by completing a frame analysis to determine the column loads transmitted to the mat. However, unless a settlement profile was assumed the loads were based on zero differential settlement. A constitutive relationship for the soil was therefore not directly invoked, nor was compatibility between the elements considered.

Differences of opinion arose when use was made of solutions for a beam or plate on an "elastic" foundation as a model of the raft. The European school favoured the linear elastic continuum model whereas many US designers considered that the spring (Winkler) model was an effective computational representation of the soil behaviour (Reti, 1967). At this stage there was little hard data which could resolve the different opinions, but it does appear that use of either model, combined with adequate experience, have not led to particular deficiencies in the design of the raft. It is clear, however, that the influence of each element of the system needs to be considered. Sommer (1965), Chamecki (1956), Grasshoff (1959) Meyerhof (1974), were amongst the first research workers who drew attention to the interactive roles of the structure and foundation, and this led to increased appreciation and activity in interaction studies.

Rutenberg (1973), in discussion of an early structure soil interaction analysis, (Lee and Brown, 1973) drew attention to the fact that a soil structure interaction analysis based on the Winkler model could be obtained by a structural frame program in which the foundation "springs" were represented by compressible, closely spaced, columns. This is an analagous interaction technique to the use of single compressible structural members to model the load-settlement behaviour of isolated footings. This technique does not appear to be adaptable to model a continuum although Hooper (1974) suggested the possibility of varying the spring stiffness over the contact area..

In a series of papers Hain and Lee (1974, 1976, 1978), using the sub-structure technique of analysis, compared the settlements and bending moments obtained by interaction analysis incorporating either the Winkler or a linear elastic continuum model. The raft was modelled as a thin elastic plate. Although predicted settlement profiles differed, the distribution and magnitude of the maximum bending moments for a moderately flexible raft were comparable. This, perhaps, explains the apparently satisfactory experience with both models, and is a matter which is further considered in this paper on the basis of other soil models.

To illustrate the likely influence of structural stiffness on settlements, column loads and moments, Hain and Lee analysed a seven storey three bay by three by framed structure and a three bay be six bay framed stuctures. (Hain and Lee, 1974; Hain, 1977). These analyses showed that the total settlement predicted by use of the linear elastic model was not sensitive to the structural stiffness but, as anticipated, the differential settlements and raft moments are greatly influenced by the structure. A re-analysis of the same 3 bay by 3 bay framed structure (Wardle and Fraser, 1976) confirmed these features.

Analyses also suggested that the structural stiffness of a multi-bay, multi-storey building approaches a "rigid" state with a limited number of storeys. The term "rigid" is meant to imply that the structure forces equal settlements at each column-raft connection. Thus it was suggested (Lee, 1976) that a simple technique for modelling the structural stiffness was the use of a rigid beam located at the first storey level. Meyerhof (1953) developed an analysis of the frame to establish an equivalent flexural stiffness and introduced the possibility of adding this stiffness to the raft stiffness-termed an "equivalent" raft.

Finite element modelling of the soil was first applied to the interaction problem in the 1960's and progressively developed (for example, Cheung and Zienkiewicz, 1965; King and Chandrasekaran, 1974; Svec, 1972, 1974, 1976; Ottaviani, 1975; Hooper, 1978). The surface element technique (Fraser and Wardle, 1976) provided solutions for the settlement profile of a flexible raft on a finite linear elastic uniform or a non-homogeneous soil layers. This approach can greatly reduce the run time compared with an analysis using typical three-dimensional quadrilateral iso-parametric multi-node elements. Commercially available structural programs, incorporating linear elastic finite layers, are now emerging. However, when a more detailed study is attempted, which takes into account a non-linear constitutive relationship, the soil stiffness will vary with vertical and horizontal position of an element due to the dependancy of the stiffness on initial and final effective stress states and stress, or strain, path (Lo and Lee, 1990; Lee, Chu and Lo, 1992). In this case, and where local features are to be modelled, the finite element approach is appropriate.

By the mid 1980's the applicability of the range of numerical analyses of structure-raft-soil and structure-raft-soil-pile systems was well understood. Three dimensional analysis require considerable run time, but with the rapid developments in PC technology it became possible to run those programs using a linearized soil model on high speed, large capacity PC systems. Attention was then focussed on the determination of a "representative modulus" and a "representative Poisson's ratio". It was also clear that appropriate comparisons of the measured behaviour of structures with predicted values of raft or raft-pile settlements, raft bending moments, column loads, and pile loads, were necessary in order to establish the effectiveness of analytical predictions.

Pressuremeter testing is now a commonly used source of in-situ stiffness data. Also, developments in control technology have made it possible to closely model the loading sequence of a soil element by controlled triaxial stress or strain path tests, (Menzies, 1987; Lee, Chu and Lo, 1991). Multi-axial testing has now been successfully developed in research studies, for example, (Lo, Chu and Lee, 1992) and given the resources could provide more appropriate stress state and path modelling. Present indications are that the triaxial data is adequate in practical cases. The decision to be made is the type of analysis and the extent of the field and laboratory studies suitable for a particular structure and site. It is noted that the stiffness characteristics at any point in the soil layer can be determined by the field/laboratory investigations, but the numerical analysis requires successive approximations to establish the modulus and Poisson's ratio specific to the initial and final effective stress states, and stress path. Lee and White (1984) recommended a constant stress increment ratio path as a reasonable and expedient laboratory test. Convergence to the appropriate modulus and Poisson's ratio is generally rapid, but this process clearly involves a considerable increase in computer capacity and run time compared with single representative values of modulus and Poisson's ratio.

Field measurements of raft and raft-pile foundation systems have been carried out with varying success. Notable reviews of the instrumentation and performance measurements of several raft-pile foundation systems include Hooper, (1973), Cooke et al (1981), Sommer et al (1985), Burland and Kalra (1986), Zhao et al, (1989), He and Jin, (1990). Such data has provided a data bank for evaluating the likely accuracy of the analytical predictions. However, experience has shown that satisfactory measurements of contact pressures, pile loads, settlement profiles, and raft moments are extremely difficult to achieve. Thus there is likely to be some unresolved questions regarding the comparison of predicted and measured values (for example, Hooper, 1973).

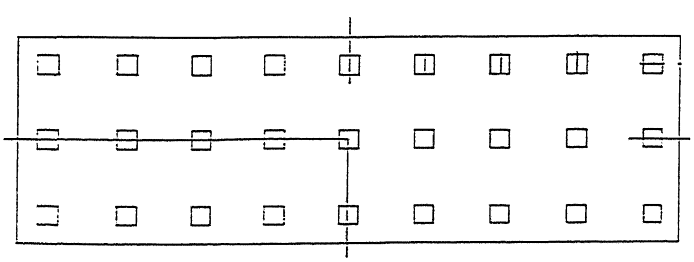
The question of the most appropriate constitutive relationship for the soil layer has not been satisfactorily resolved, but predictions are likely to be less sensitive to the type of constitutive model when all the elements of the system are taken into account.

The present paper concentrates initially on the application of the interaction analysis to predict the effect of varying site conditions. A review is made of selected case studies. Particular attention is then paid to the consequences of the type of soil model selected for the analysis.

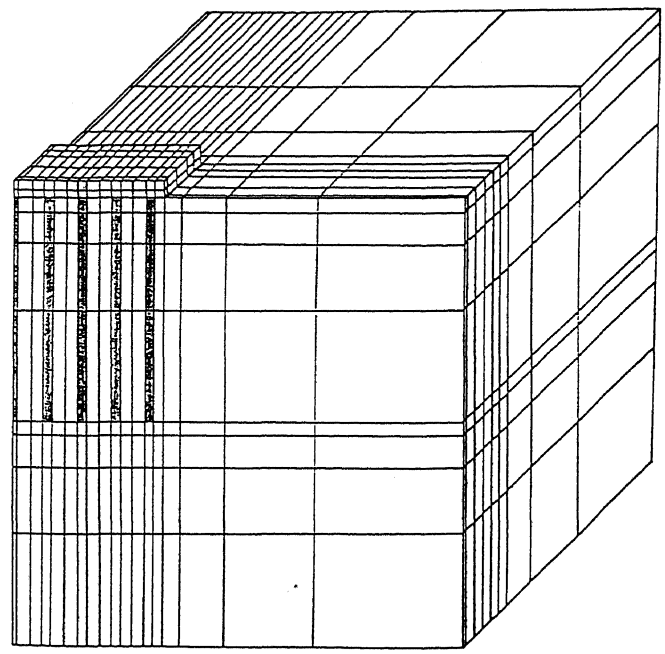
Analysis of Site Features

With the satisfactory development of the numerical interaction analysis, it is possible to include the effects of particular features of a site on the performance of raft and raft-pile systems. Some recent analysis will be quoted, based on a finite element "representation" of the structure, raft and soil and pile elements. It needs to be mentioned that this finite element analysis was developed as a tool for a research orientated study considering the influence of the soil model on overall structural behaviour. Three dimensional iso-parametric quadrilateral elements with eight nodes were used for all elements of the system. Figs. 1(a), (b), (c) show the configuration of the structure, raft, soil, and pile elements of one structural system examined in some detail. Reference will be made to the results of analyses incorporating all or some of these elements.

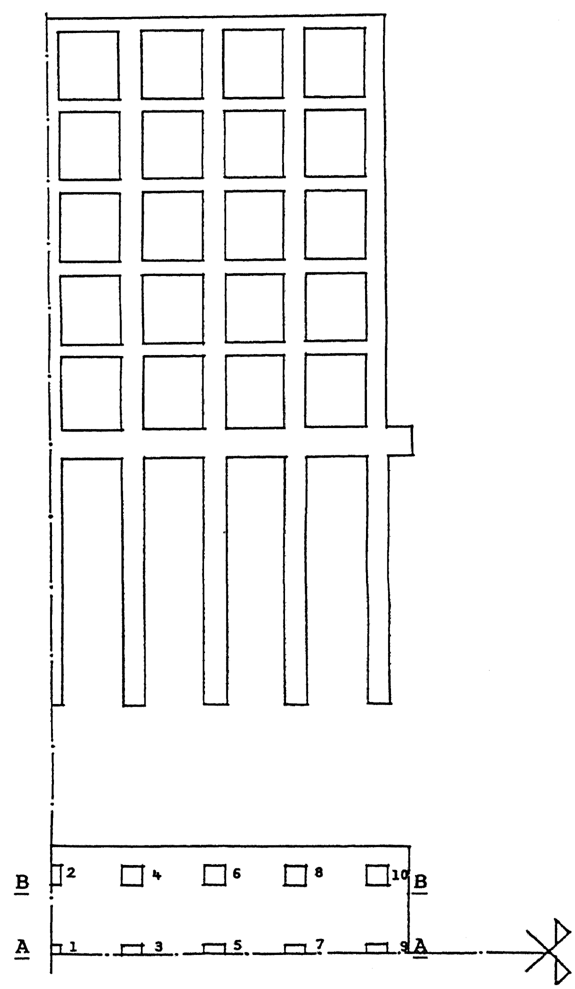
Initially, consider the apportionment of total load between the pile group and the raft. Fig. 2 shows the effect of raft stiffness, pile spacing and pile length on the proportion of the total load, P_p, carried by the pile group when the effect of the structure is ignored. The piles are of moderate compressibility. It is seen that an essentially rigid raft ($K_r = 10$) carries only about 5% more of the total load than a flexible raft ($K_r = 0.001$). Both an increase in the number of piles and an increase in length/diameter ratio significantly increases P_p since each contributes to the overall stiffness of the pile group.



Figs. 1 (a) Location of Columns and Piles



(b) Finite Element Modelling of Raft-Pile



(c) Structure

When the effect of the structure is considered there are changes in the distribution of column load. The influence of structural stiffness on individual loads is shown in Fig. 3, where the "structural stiffness" is expressed in terms of the number of storeys. It is noted:

(i) the influence of reduced raft stiffness is to increase the loads carried by the outer columns as a consequence of a concave settlement profile,

(ii) the convergence of column loads to values associated with a "rigid" structure.

The combined effect of the distribution of column loads, pile loads, and contact pressure distribution on maximum lateral bending moment in the raft is shown in Fig. 4 for a range of pile stiffness, raft stiffness, and structural stiffness. The dominant influences are the latter two variables.

The structural stiffness also has relatively little effect on P_p - in the present case the load carried by the pile group is reduced by a maximum of about 5%.

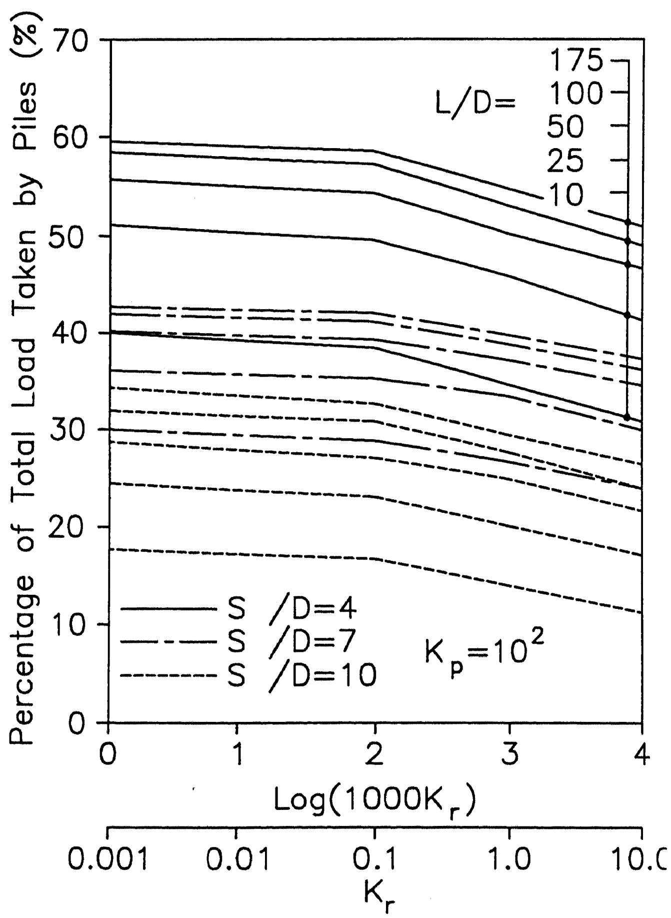


Fig. 2 Proportion of Total Load Supported by Pile Group (P_p). Linear Elastic Analysis.

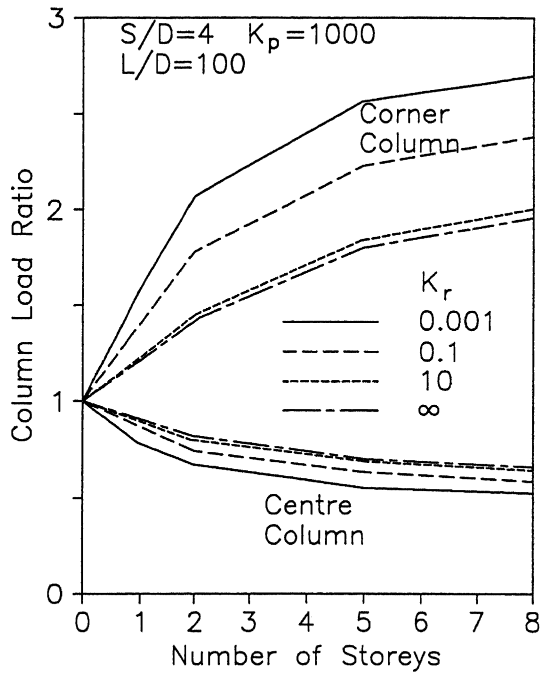


Fig. 3 Distribution of Column Loads Raft-Pile. Linear Elastic Analysis.

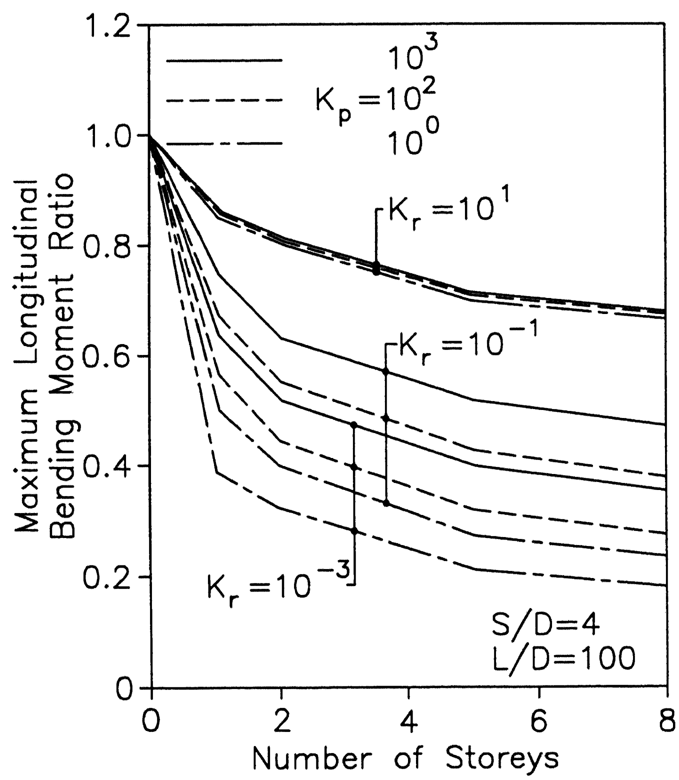


Fig. 4 Maximum Longitudinal Bending Moment Raft-Pile. Linear Elastic Analysis.

Non-Homogeneous and Layered Deposits

Analysis of a raft on a deposit with increasing strength and stiffness with depth (the "Gibson" model) (for example, Hooper, 1973; Hain and Lee, 1978), and a raft on single and multi-layered deposits (for example, Fraser and Wardle, 1976) have been thoroughly developed. Use can be made of the multi-layered solutions to model any stiffness profile. Fig. 5 illustrates the effect of increasing stiffness with depth on the maximum settlement of a uniformly loaded, flexible, rectangular, raft. Maximum bending moments are shown in Fig. 6 for the Gibson soil and in Fig. 7 for a two layered deposit.

The expressions and notations used in the Figs.5 to 7 are:

$$K_r = \frac{4\ E_r\ t_r^3\ B\ (1 - \nu_s^2)}{3\ \pi\ E_o\ L^4}$$

$$Y = \frac{E_o}{q\ \sqrt{B.\ L}\ (1 - \nu_s^2)}$$

$$Z = \frac{1000}{q\ L\ B}$$

where
- B = width of raft
- L = length of raft
- t_r = equivalent thickness of raft
- E_o = soil modulus at surface
- E_L = soil modulus at depth equal to 0.5 L_r
- ν_s = Poisson's ratio of soil
- q = uniform pressure

Fault Model

Where faulting leads to exposure of soils of different stiffness beneath a raft, there is a rapid transition of contact stress in the vicinity of the fault. This is illustrated in Fig. 8 for a single vertical fault. There is, of course, a rotation due to the different compressibilities on either side of the fault.

Contact pressure distributions are shown along the major centreline and along the length at a section close to the edge. For comparitive purposes the distributions for a homogeneous soil are also shown. The fault is located at the centreline with values of modulii of E_1 and E_3 on either side of the fault.

Stepped Raft

There is only a very limited amount of published information on the detailed analysis of a stepped raft. Contact pressure distributions along the centre line and length of such a raft are shown in Fig. 9. The influence of the local disturbance diminishes with increasing raft stiffness. In the case studied (see inset Fig. 9) the maximum positive bending moment was up to 10% less than the corresponding value for a plane raft. The moments are not sensitive to the magnitude of the step.

When the stepped raft is used in conjunction with a pile group the pile group appears to support slightly smaller load than that associated with a plane raft combined with piles. For the case illustrated the maximum difference was about 5%. Settlements and raft bending moments are slightly reduced.

Selected Case Studies

Of the several performance studies published some have sufficient data for an interaction analysis and hence a comparison of the predicted and measured performance can be completed. One such case is a 30 storey building supported on two (17.5m x 22.5m x 2.5m thick) raft-pile foundation (42 piles) (Sommer et al, 1985). The soil profile consisted of a 2.5m layer of gravel beneath the raft, overlying a deep non-homogeneous layer of Frankfurt clay. Instrumentation included in depth extensometers, contact pressure cells across the short axis of the raft at the centre and near the edge, and instrumented piles at the centre, mid-point at the edge of the longer dimension, and at a corner.

Due to limitations of available structural details, the structural stiffness was modelled by a rigid beam located at first storey level. Fig. 10 compares the predicted and measured pile loads along the short centre line and near the edge. Note the lack of symmetry due to a resultant load eccentricity of 0.8m. Comparative settlement profiles over a depth of 42.5m are shown in Fig. 11. Table 1 is a summary of the comparative data. It is noted that the most critical test of the accuracy of the prediction would be a bending moment comparison.

Hooper and Wood (1976) used an elastic analysis to analyse a 22 storey residential building of cross wall construction supported on a 0.76m thick raft. The soils immediately beneath the raft were 5m of gravel overlying 25m of London clay. The average raft pressure was 246 kPa. In order to take into account the effect of structural stiffness, the relative stiffness of the raft was increased ("equivalent" raft). The measured time-settlement curve was bounded by the computed curves corresponding to the undrained and drained states.

Hain and Lee (1978) re-analysed the Latino Americano building constructed in Mexico City and obtained reasonable correlations on the basis of available performance data.

Hooper (1973) obtained close correlation between predicted and recorded pile loads, contact pressures and settlements for the Hyde Park Cavalry Barracks Tower, utilizing the field data for a soil stiffness increase with depth. Measurements

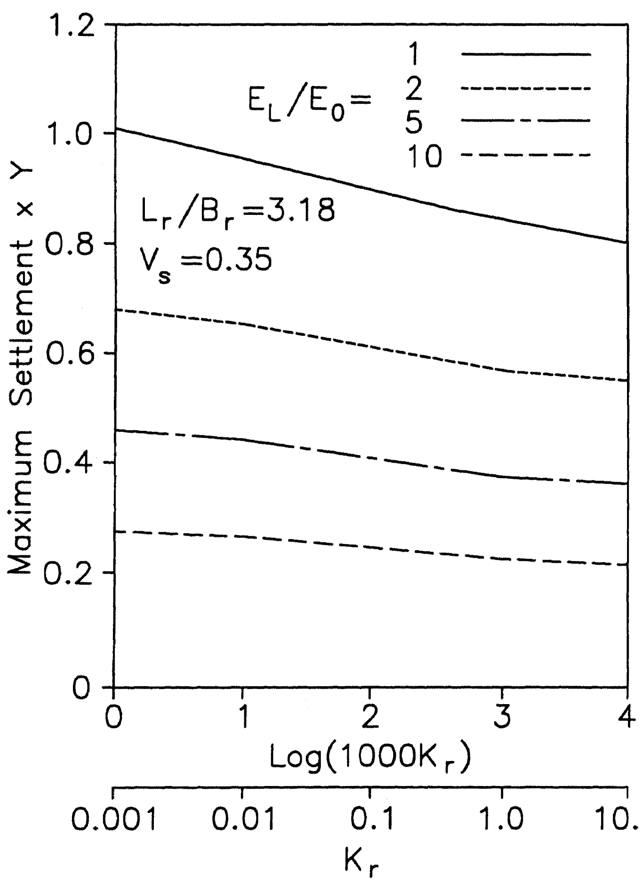


Fig. 5 Maximum Total Settlement of a Uniformly Loaded Rectangular Raft. No Structure. Gibson Model.

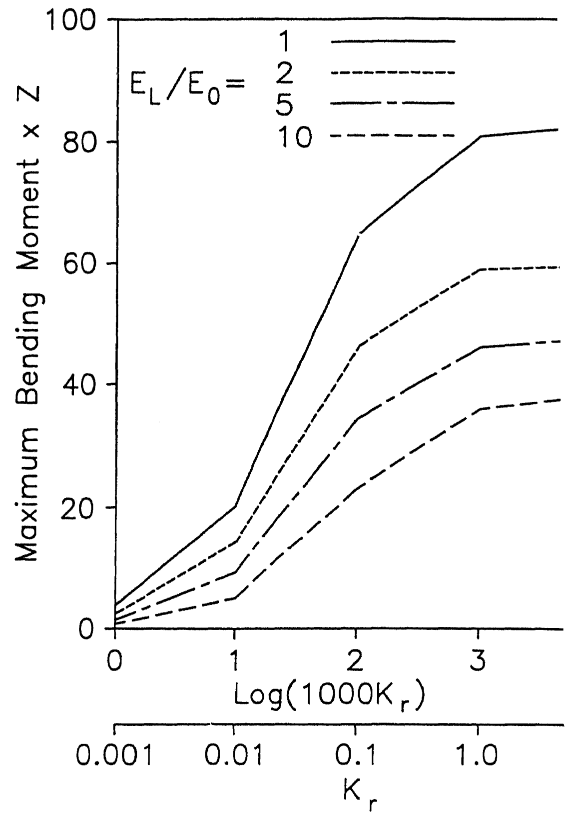


Fig. 6 Maximum Longitudinal Bending Mon Uniformly Loaded Rectangular Raft. Structure. Gibson Model.

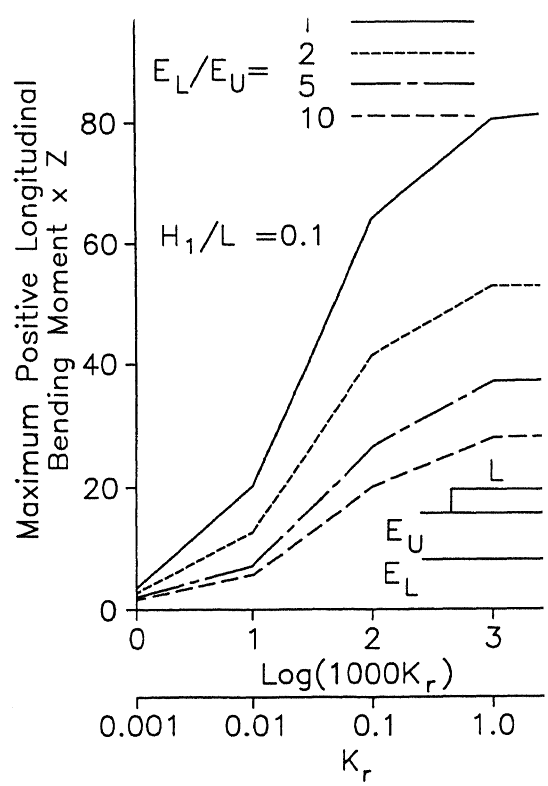


Fig. 7 Maximum Longitudinal Bending Momer Uniformly Loaded Rectangular Raft. Nc Structure. Layered Linear Elastic. Soil I

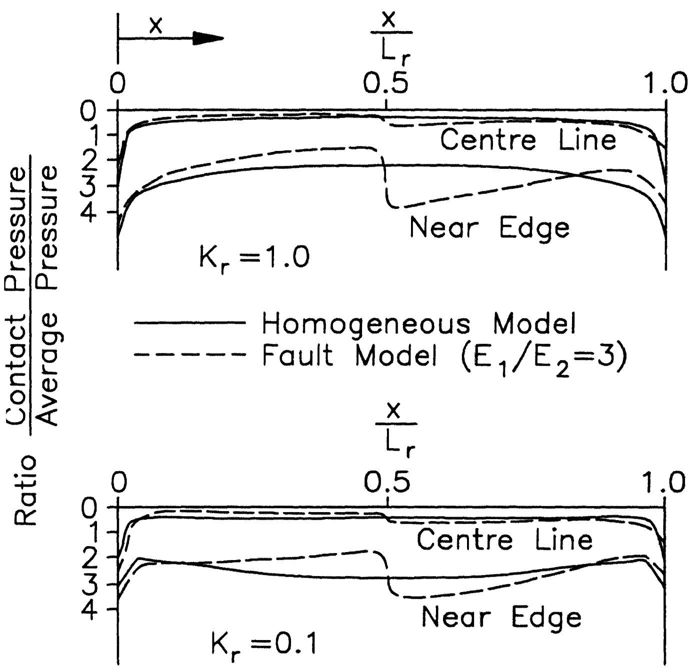
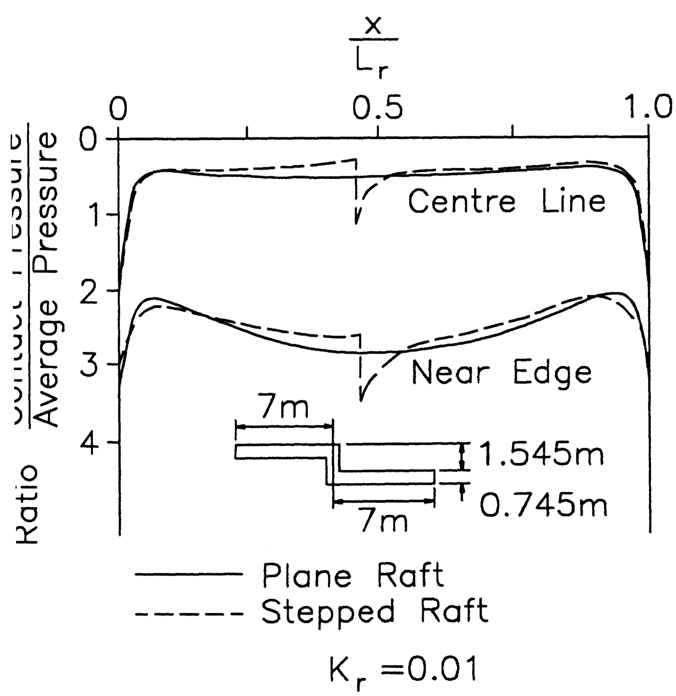


Fig. 8 Comparison of Contact Pressure Distributions for a Homogeneous and a Faulted Supporting Soil. Single Central Vertical Fault. Linear Elastic Analysis.



ig. 9 Contact Pressure Distributions. Stepped Raft. Linear Elastic Analysis.

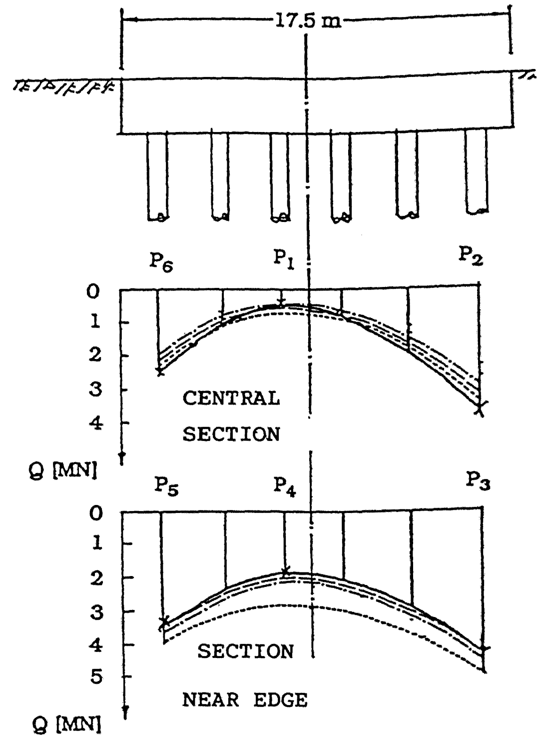


Fig. 10 Predicted and Recorded Pile Loads. Multi-Storey Building Frankfurt. Raft-Pile Foundation. Linear Elastic Analysis.

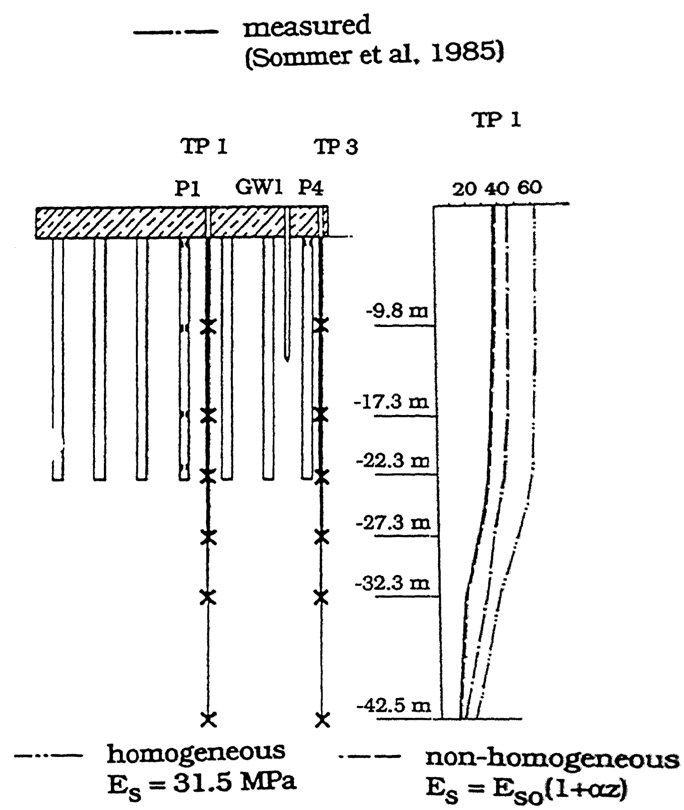


Fig. 11 Predicted and Recorded Settlements Beneath Multi-Storey Building Frankfurt. Raft-Pile Foundation. Linear Elastic Analysis.

Table 1

Comparison of Recorded and Predicted Data

Non-Homogeneous Soil Model $E_s = E_{so}(1 + \alpha Z)$

	Maximum Settlement (mm)	Differential Settlement (mm)	Maximum Bending Moment + (kN/m)	Maximum Bending Moment - (kNm/m)	P_p (%)
Predicted	39.4	2.98	1058	-433	84.3
Measured	45.0	>3 to 4	Not Measured	Not Measured	75.0

Table 2

PERFORMANCE OF STRUCTURES ON RAFT-PILE FOUNDATION

Building No.	1	2	3	4	5	6	7	8
Superstructure Form	Frame + Tube	Cross Wall	Cross Wall	Frame + Tube	Frame	Frame + Tube	Frame + Shear Wall	Frame + Shear Wall
No. of Storey	31	22	16	30	11	26	16	22
Foundation Type	Pile-Raft	Pile-Cap	Pile-Raft	Pile-Raft	Pile-Raft	Pile-Raft	Pile-Box	Pile-Box
Dimension of Raft (Box) (m^2)	25.0x25.0	27.5x16.58	43.3x19.2	2(22x17.5)	56x31	36.4x36.26	45.95x14.2	42.7x24.7
No. of Pile	51	48	351	2x42	29	200	203	344
Pile Length (m)	24.8	18.6	13.0	20.0	16.75	53.0	22.0	22.0
Pile Diameter (cm)	91	86	45	90	180	60.9x1.2	45x45	55x8
Pile Spacing (m)	1.9	3.08	1.60	2.70-3.15	6.9-10.0	1.90-1.95	1.65-3.30	1.7-2.0
Total Pressure (KPa)	368	232	190	468.75	235	320	240	310
Measured S_{max} (mm)	17* 22	18* 23	10* 16	45**	20	39.4	20	25
Predicted S_{umax} (mm) S_{dmax}	11.6 23.6	13.3 30.3	8.13 16.05	36.2 70.8	18.1 36.8	40.5	20.6	26.2
Measured ΔS_{max} (mm)	6.8	2.0	5.0	>3.0-4.0**	10.0	>3.4***		
Predicted ΔS_{umax} (mm) ΔS_{dmax}	3.68 6.95	2.51 5.45	4.85 9.21	4.20 8.10	9.58 17.8	3.53		
Source	Hooper (1973)	Hooper (1977)	Cooke (1981)	Sommer (1985)	Burland (1986)	Zhao (1989)	Zhao (1989)	He (1990)

* Measured maximum total settlements at end of construction.

** Measured maximum total settlement during construction.

*** Measured differential settlement between maximum and average total settlement.

established that about 60% of the total load was supported by the pile group at the end of construction. Comparisons of the predicted and measured load-time relationships were, generally, within the range of values associated with undrained and drained soil parameters. A similar concordance was shown for total and differential settlements - time relationships. Such confirmation based on data which appears to be very reliable strongly supports the use of the linear elastic model. A re-analysis was later made (Hain and Lee, 1978) based on the interaction factors for the non-homogeneous continuum although basement heave was not directly included in the analysis.

Hooper discussed the type and performance of the field instrumentation for four buildings in London and one in Rotterdam, each supported on a raft-pile system. Some conclusions based on the data from the last four buildings were not definitive, and reflected the difficulties of obtaining reliable data. Several more recent studies include structures with frame and tube (Sommer et al 1985; Zhao et al, 1989), cross wall (Cooke et al, 1981; Zhao et al, 1989) and frame plus shear wall construction (Zhao et al, 1989; He et al, 1990). There are at least two reported raft-pile systems which used a very limited number of piles, (Koizumi et al, 1967; Cook et al, 1980).

Relevant data are presented in Table 2. This table provides a summary of details of eight buildings supported by a raft-pile system. The predicted "values" of the short and long term total and differential settlements were based on a sensitivity study, using the results of the present finite element analysis. Thus the quoted values are a guide to anticipated values rather than predictions based on the details of the specific structure, as quoted on Table 1. At the time of writing analyses were being carried out on the listed structures, but apart from the Frankfurt building the analyses have not been completed and checked. It is noted that the values obtained by the detailed analysis (Table 1) and the "sensitivity" analysis (Table 2) are comparable. Furthermore, the concordance of "predicted" and measured values for the structures is generally reasonable. Similar agreement for the load appointment to the pile group was obtained.

Some selected field performance data for plain rafts are presented by Morton and Wu (1974), Eden (1977), Fraser (1975) and Sue and Zheng (1984). Data are presented in Table 3. Again, "predicted" values are reasonably consistent with measured values. Detailed analyses of each structure are being made.

Soil Moaeıs and Interaction

Consideration will now be concentrated on the influence of the chosen soil model on the predicted settlements, column loads and bending moments for an unpiled raft, and the settlements, bending moments, column loads, proportion of load taken by the pile group, and the distribution of pile loads, for a raft-pile system. Comparisons will be made between the predicted values with and without a structure, and with and without piles.

Various soil models could be considered. Those chosen for use in the interaction analysis are the well established Duncan-Chang and Lade models. Predicted values using these two non-linear models will be compared with the linear elastic predictions. Similar studies can, of course, be made using any of the constitutive models developed over the last several decades.

Table 3

PERFORMANCE OF STRUCTURES ON A RAFT FOUNDATION

Building No.	1	2	3	4	5
Superstructure Form	Cross Wall	Cross Wall	Frame + Shear Wall	Frame	Plate wall
No. of Storeys	22	22	15		
Foundation Type	Raft	Raft	Raft	Raft	Box
Dimension of Raft (Box) (m^2)	27.5x16.6	27.5x16.6	29.4x18.66	42x42	46.5x46.5
Total Pressure (KPa)	246	250	133	307	129
Measured S_{max} (mm)	64** 90***	110	30	24	1666
Predicted S_{umax} (mm) S_{dmax}	63.5 114	59.8 103.9	27.1 47.9	27.1	1647-2022*
Measured ΔS_{max} (mm)	20.5** 22.6***	>10	15	13	
Predicted ΔS_{umax} (mm) ΔS_{dmax}	15.2 27.5	11.3 21.7	7.48 14.4	13.47	
Sources	Morton & Wu (1974)	Morton & Wu (1974)	Eden (1977)	Fraser (1975)	Sue & Zheng (1984)

* Maximum total settlement corresponding to the range of raft stiffness, K_r, from 0.01 to 10.0

** Maximum total settlement at end of construction

*** Maximum total settlement after 6.4 years.

Unpiled Raft

Use of either the Duncan-Chang or the Lade model predicts a contact pressure distribution which is more uniform than the traditional linear elastic distribution. The two non-linear models also predict that the uniformity increases with an increase in total load. Fig. 12 shows the contact pressures for a rectangular, flexible, raft supported by a deep layer of granular soil. Parameters for the Lade model are those for the crushed Napa Basalt (Lade 1977). A consequence is a reduction in the positive bending moments compared with values predicted by use of the linear elastic model.

In order to make direct comparisons of the effects of the different models it is necessary to establish the relevant parameters for the given soil. As an example, the data quoted by Lade for a loose Sacramento river sand was also sufficient to obtain the Duncan-Chang parameters and to estimate the linear elastic parameters. The chosen raft had an aspect ratio of 3.1 and a thickness of 1.0m thus the calculated values apply to a flexible raft. The stiffness of the structure was close to rigid.

The effect of the structural stiffness on the maximum total settlement was small but, of course, has a significant effect on the differential settlements and the distribution of column loads. A comparison of Fig. 13(a) and Fig. 13(b) illustrates the influence of the structural stiffness on the differential settlements, as predicted by the three models. When the influence of the structure is considered the raft bending moments reflect the redistribution of column loads away from the central sections as a consequence of the concave settlement profile. This leads to a significant reduction in positive bending moments (Figs. 14(a), 14(b)).

Piled Raft

For the comparitive purposes, consider the consequences of combining the rectangular raft with a pile group. Analyses were completed using the three soil models for a pile spacing - diameter ratio of 4, and a length-diameter ratio of 100. The raft thickness was maintained at 1.0m. Pile stiffness, K_p, was 100. Limitations could be placed on the ultimate bearing capacity of individual piles using a technique previously developed (Hain and Lee, 1978). The following results are limited to the situation where all piles have not reached the ultimate load capacity.

Calculated values of the differential settlements are plotted in Fig. 15(a) for the raft-pile without consideration of the structural stiffness and Fig. 15(b) is the corresponding plot when the structural stiffness is included in the analysis. Predicted values of the maximum bending moments with and without consideration of the structural stiffness are shown in Figs. 16(a) and 16(b), respectively. It is seen that the maximum bending moments are insensitive to the structural stiffness. This feature arises because of the combined effects of changes in both the column loads and the pile loads.

Fig. 17 illustrates that the same feature was evident in a separate group of analysis using the Lade parameters for the Napa basalt. In this case the maximum bending moments were only slightly reduced by the effect of the structure and the close similarity of calculated values was common to the range of raft thickness of 0.6m to 2m. Comparisons of corner pile loads (P_c) with and without the structure show there is a significant effect of the structural stiffness and this effect ranges from zero for a rigid raft to some 25% for the flexible (0.6m) raft. There are corresponding changes in other pile loads and Fig. 18 includes a plot showing the effect of the structural stiffness on the load taken by a pile located at the centre of the raft (P_i). Values of load are expressed as a ratio of the average load.

The proportion of the total load is, however, not sensitive to the structural stiffness for the range of raft stiffness. This is illustrated in Fig. 19 for the particular pile group. Figs. 18 and 19 are also based on the Lade parameters for the Napa basalt.

As with the plain raft the deflection bowl is concave, hence the structural stiffness will cause a transfer of column loads from the interior to the outer sections of the raft.

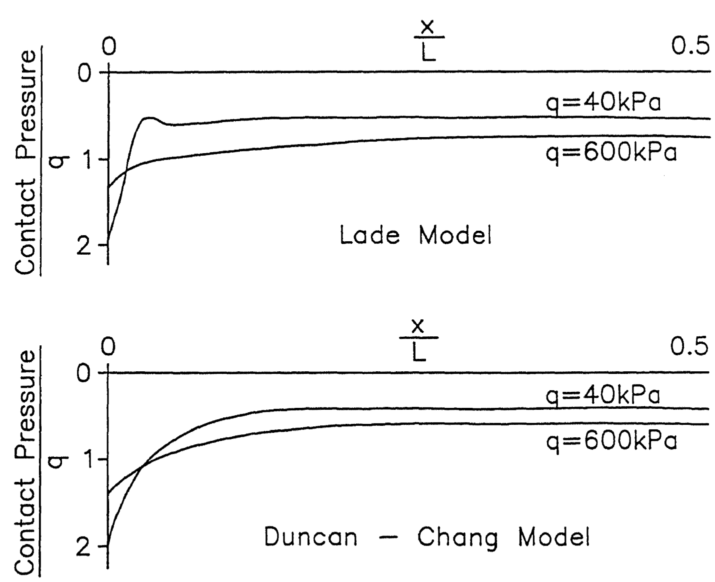


Fig. 12 Contact Pressure Distribution. Unpiled Flexible Raft. Lade and Duncan-Chang Models. Napa Basalt Supporting Soil.

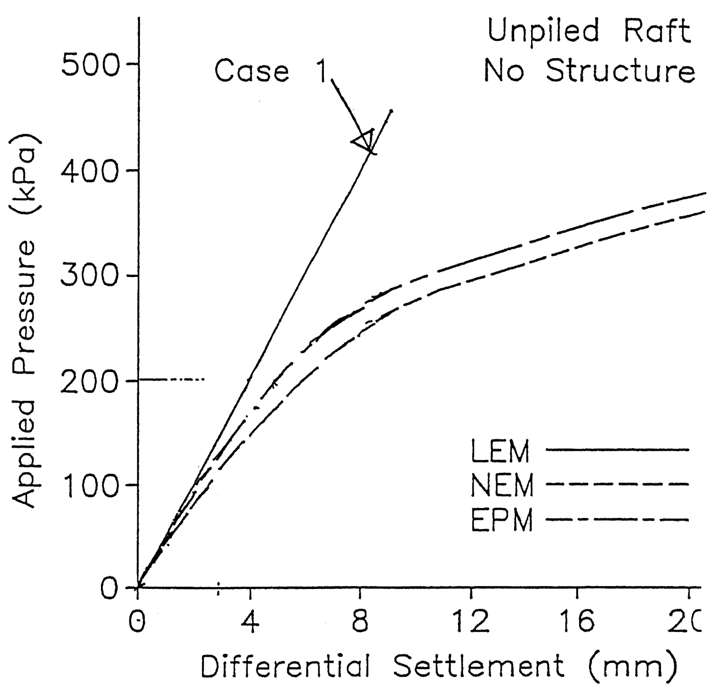


Fig. 13 (a) Predicted Differential Settlements. Raft. No Structure. Linear Elastic, Lade, Duncan-Chang Models. Loose Sacramento Sand.

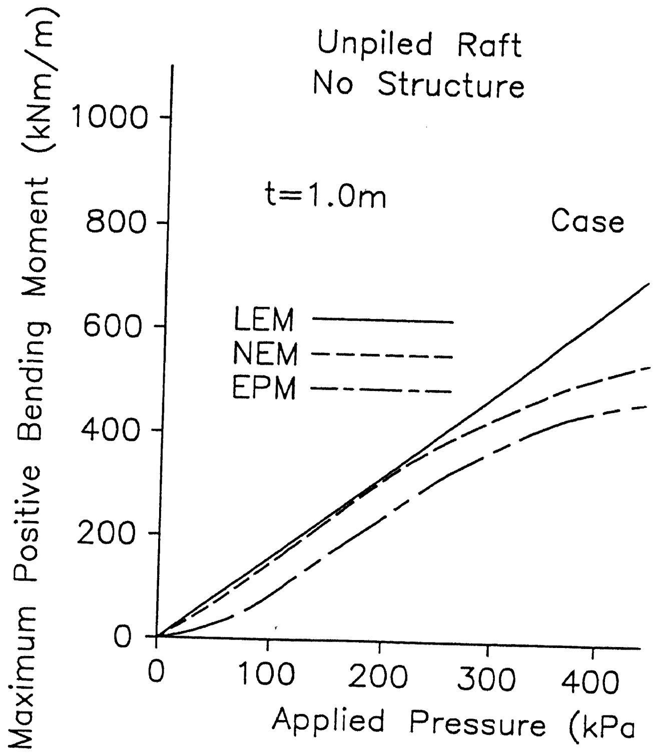
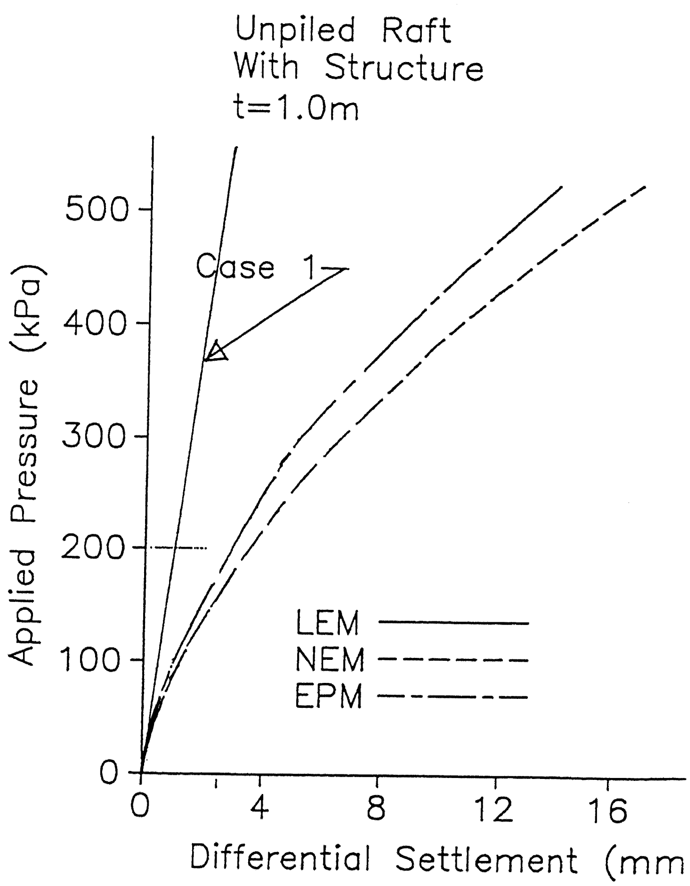
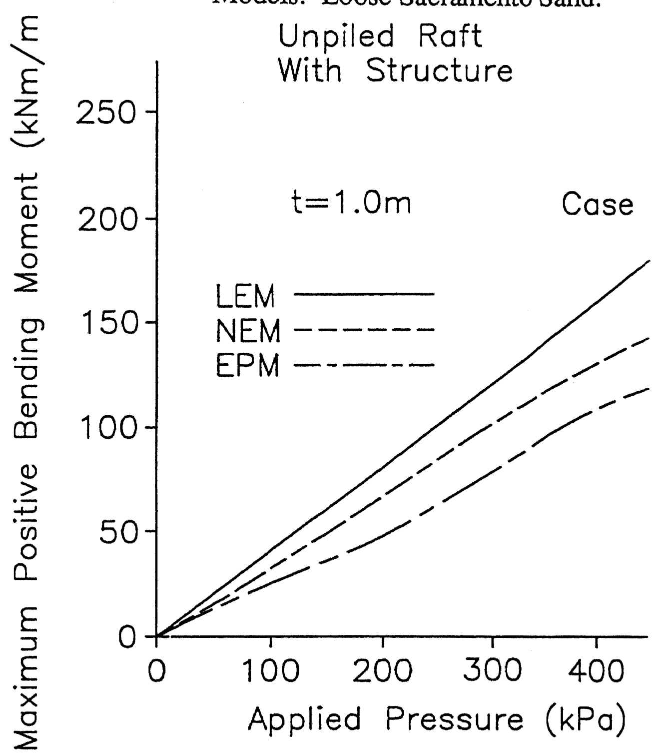


Fig. 14 (a) Maximum Longitudinal Bending Moments. Raft. No Structure. Linear Elastic, Lade, and Duncan-Chang Models. Loose Sacramento Sand.



(b) Differential Settlements. Structure-Raft Linear Elastic, Lade, Duncan-Chang Models. Loose Sacramento Sand.



(b) Maximum Longitudinal Bending Moments. Structure-Raft. Linear Elastic, Lade, and Duncan-Chang Models. Loose Sacramento Sand.

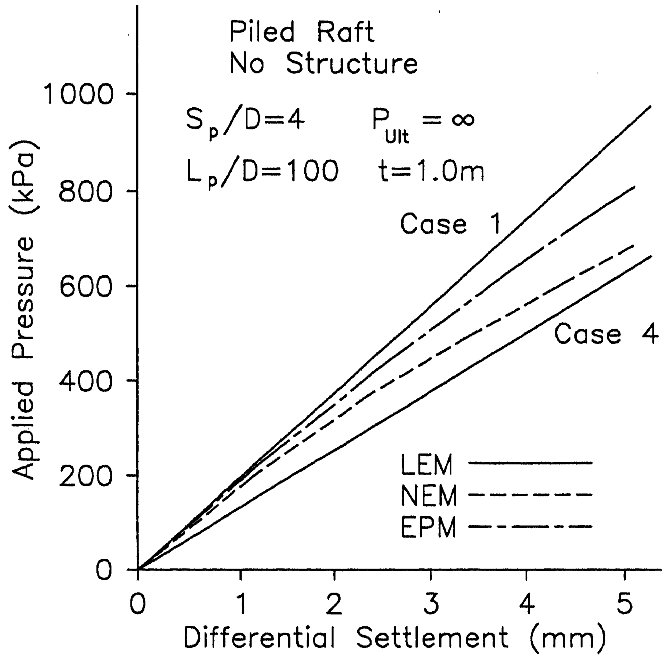


Fig. 15 (a) Differential Settlements. Raft-Pile. Linear Elastic, Lade, Duncan-Chang Models. Loose Sacramento River Sand.

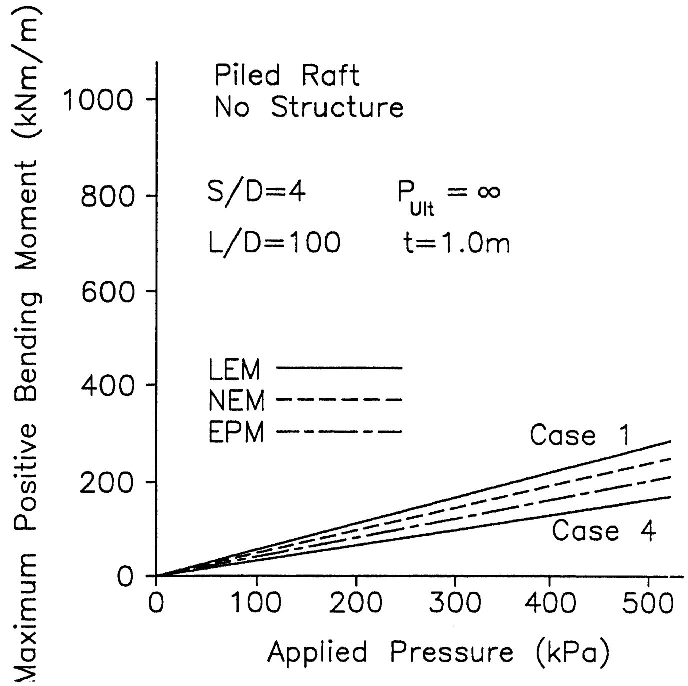
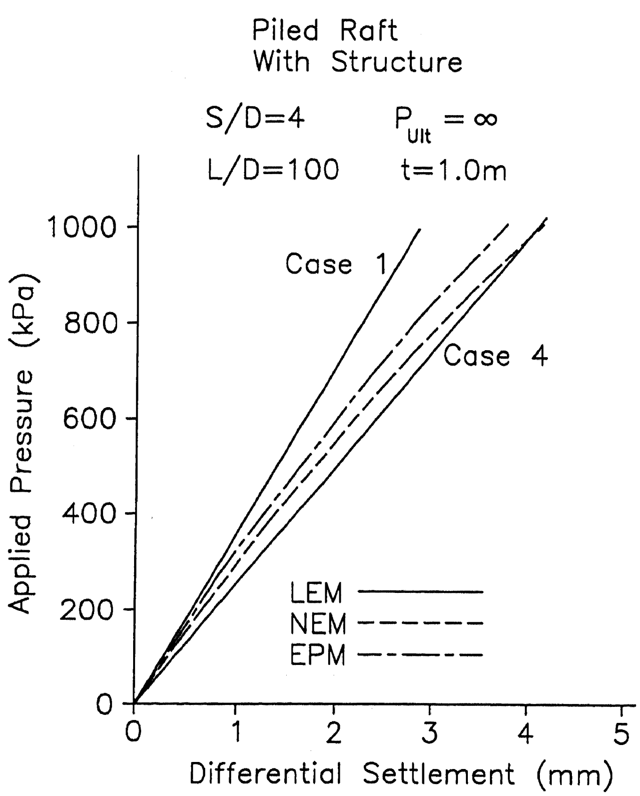
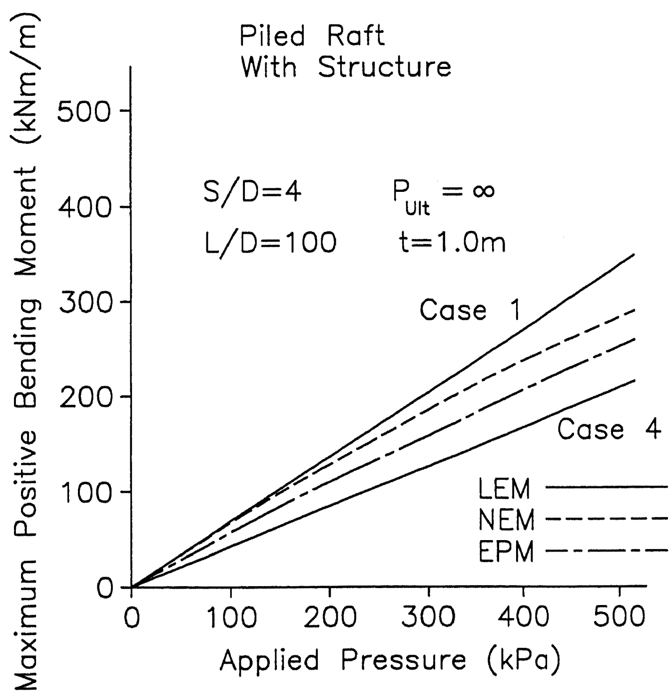


Fig. 16 (a) Maximum Positive Bending Moments. Raft-Pile. Linear Elastic, Lade, Duncan-Change Models. Loose Sacramento River Sand.



(b) Differential Settlements. Structure-Raft-Pile. Linear Elastic, Lade, Duncan-Chang Models. Loose Sacramento River Sand.



(b) Maximum Positive Bending Moments. Structure-Raft-Pile. Linear Elastic, Lade, Duncan-Chang Models. Loose Sacramento River Sand.

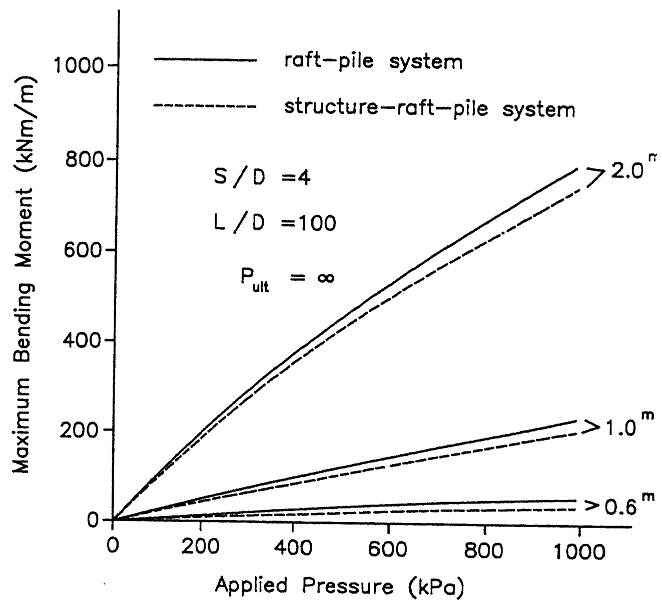


Fig. 17 Influence of Structural Stiffness on Maximum Positive Bending Moment in a Piled Raft. Lade Model. Napa Basalt.

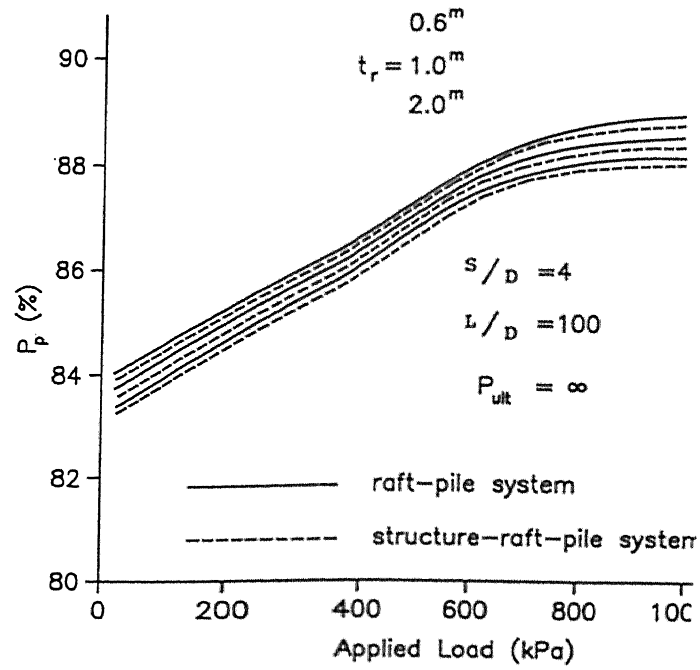


Fig. 19 Influence of Structural Stiffness on Load Apportionment. Lade Model. Napa Basalt.

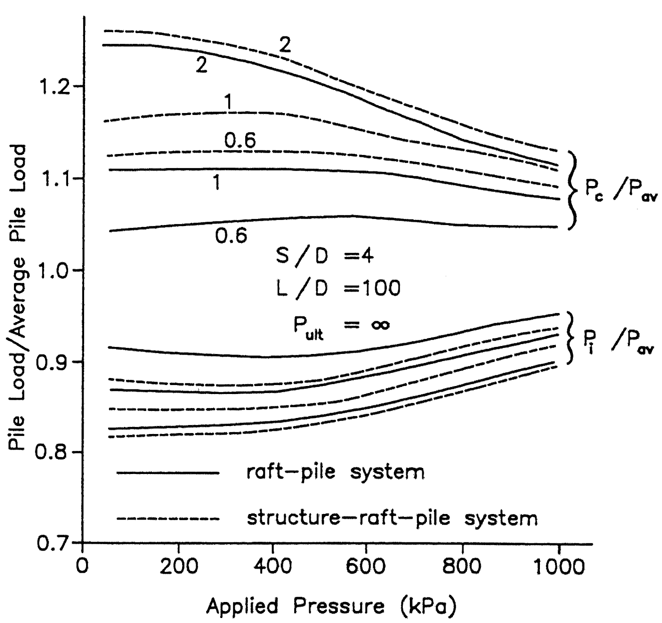


Fig. 18 Influence of Structural Stiffness on Distribution of Pile Loads. Lade Model. Napa Basalt.

CONCLUDING REMARKS

Various types of interaction models and numerical techniques have been highly developed and used to analyse and design numerous multi-storey structures supported on a raft or raft-pile system. Selected structures have been instrumented to record column loads, pile loads, contact pressures, total and differential settlements. Comparisons of predicted and measured values have provided consistent evidence that linear elastic modelling of the elements can provide values which are in good agreement with corresponding measured values.

Predictions based on other soil models such as the Lade and Duncan-Chang model, for example, give similar results to the linear elastic model provided the parameters are appropriately determined.

References

Burland, J.B. and Kalra, J.C. (1986) "Queen Elizabeth II Conference Centre: Geotechnical Aspects" Proc. Inst. Civil Engs., Part I, 80, 1497 - 1503.

Chamecki, S. (1956) "Structural Rigidity in Calculating Settlements", Jnl. Soil Mech. and Foundation Div., ASCE, 82, SM1, 1 - 9.

Cheung, Y.K. and Zienkiewicz, O.C. (1965) "Plates and Tanks on Elastic Foundations - An Application of Finite Element Method" Int. Jnl. Solids Structures, 1(4), 451 - 461.

Chu, J., Lo S-C.R. and Lee, I.K. (1993) "Instability of Granular Soils Under Strain Path Testing" To be published in Jnl. Geot. Div., ASCE.

Cooke, R.W., Smith, D.W., Gooch, M.N. and Sillet, D.F. (1981) "Some Observations of the Foundation Loading and Settlement of a Multi-Storey Building on a Piled-Raft Foundation in London Clay" Proc. Inst. Civil Engs., Part 1, 70, 433 - 460.

Cooke, R.W., Price, G. and Tarr, K.W. (1980) "Jacked Piles in London Clay: Interaction and Groups Behaviour Under Working Conditions" Geotechnique, 30(2), 449 - 471.

Eden, W.J., McRostie, G.C. and Hall, J.S. (1973) "Measured Contact Pressures Below Raft Supporting a Stiff Building" Can. Geotech. Jnl., 10, 180, 180 - 192.

Fraser, R.A. (1975) "Review of Investigation of Raft Foundation for Major Buildings on Deep Soil, Perth Area" Proc. Symp. Raft Foundations, Perth, 23 - 40.

Fraser, R.A. and Wardle, L.J. (1976) "Numerical Analysis of Rectangular Rafts on Layered Foundations" Geotechnique, 20(4), 613 - 630.

Grasshoff, H. (1959) "Influence of Flexural Rigidity of Superstructure on the Distribution of Contact Pressure and Bending Moments in an Elastic Combined Footing" Proc. Fifth Int. Conf. Soil Mech. and Fdn. Eng., 2.

Hain, S.J. and Lee, I.K. (1974) "Rational Analysis of Raft Foundations" Jnl. Geot. Div., Proc., ASCE, 100, No. GT7, 843 - 860.

Hain, S.J. and Lee, I.K. (1978) "The Analysis of Flexible Raft-Pile Systems" Geotechnique, 28(1), 65 - 83.

Hain, S.J., Valliappan, S. and Lee, I.K. (1976) "Analysis oi Rafts on Non-Homogeneous, Non-Linear Soil". Proc. Second Int. Conf. on Finite Elements, Adelaide, Australia.

He, Y.H. and Jin, B.S. (1990) "The Interaction Between Pi and Soil of Box-Foundation with Friction Pile-Group for Highrise Buildings" (in Chinese), Chinese Journal of Geotechnical Engineering, 12(3), (Total No. 56), 53 - 65.

Hooper, J.A. (1973) "Observations on the Behaviour of a Piled-Raft Foundation on London Clay", Proc. Instn. Civil Engrs, 55, 855 - 877.

Hooper, J.A. (1974) "Analysis of Circular Raft in Adhesive Contact with a Thick Elastic Layer" Geotechnique, 24(4), 691 - 711.

Hooper, J.A. (1978) "Foundation Interaction Analysis, Developments in Soil Mechanics - 1" (Ed. C.R. Scott), Applied Science Publications (London), Chapter 5, 149 - 211.

King, G.J.W. and Chandrasekaran, V.S. (1974) "An Assessment of the Effects of Interaction Between a Structui and its Foundation" Proc. British Goetech. Soc. Conf. on settlement of Structures, Cambridge, 368 - 383.

Korzumi, Y. and Ito, K. (1967) "Field Tests with Regard tc Pile Driving and Bearing Capacity of Piled Foundation" Soils and Foundation, 7(3), 30 - 53.

Lee, I.K. (1976) "Interaction Analyses of Raft and Raft-Pil Systems" Proc. Conf. Soil Structure Interaction, Roorkee, India, 513 - 520.

Lee, I.K. and Brown, P.T. (1972) "Structure - Foundation Interaction Analyses" Jnl. of the Structural Div., ASCE, Vo 98, No. ST11, Proc. Paper 9352, Nov., 2413 - 2431.

Lee, I.K., Chu, J. and Lo, S-C.R. (1992) "Response of a Granular Soil During Strain Path Testing". Int. Workshop on "Modern Approaches to Plasticity", Horto, Greece.

Lee, I.K., White, W. and Bremner, W. (1984) "Prediction of Settlements of Large Oil Storage Tanks" Proc. 3rd Conf. on Ground Movements and Structures, Uni. of Wales, Inst. Science and Technology.

Lo, S-C.R. and Lee, I.K. (1990) "Response of a Granular Soil Along Constant Stress Increment Ratio Path" Jnl. Geotech. Div. Proc. ASCE, 116(3), 355 - 376.

Lo, S-C.R., Chu, J. and Lee, I.K. (1991) "Multi-Axial Stress-Strain Path Testing on Dense Granular Soil" Research Reports R95, R100 and R109, Department of Civil & Maritime Engineering, University College, UNSW, Canberra, Australia.

Menzies, B.K. (1987) "A Computer Controlled Hydraulic Testing System", Proc. ASTM, Symp. on Advanced Triaxial Testing, 82 - 94.

Morton, K. and Au, E. (1974) "Settlement Observations on Eight Structures in London" Proc. Conf. Settlement Structures, Cambridge, 183 - 203.

Ottaviani, M. (1975) "Three-Dimensional Finite Element Analysis of Vertically Loaded Pile Groups" Geotechnique, 25(2), 159 - 174.

Reti, A.A. (1967) "Discussion of Report of ACI Comm. 436" Jnl. ACI, 64(6).

Rutenburg, A. (1973) Discussion on Paper "Structure - Foundation Interaction Analysis" by I.K. Lee and P.T. Brown (Proc Paper 9352). Sept 1973.

Sommer, H. (1965) "A Method for the Calculation of Settlements, Contact Pressures, and Bending Moments in a Foundation Including the Influence of the Flexural Rigidity of the Superstructure" Proc. Sixth. Int. Conf. Soil Mechanics and Fdn. Eng., 2, 197 - 201.

Sommer, H., Wittmann, P. and Ripper, P. (1985) "Piled Raft Foundation of a Tall Building in Frankfurt Clay" Proc. 11th Int. Conf. on SMFE, 2253 - 2257.

Sue, G.S. and Zheng, D.T. (1984) "Soft Ground Foundation and Underground Engineering" Chinese Architectural and Industrial Press.

Svec, O.J. (1974) "The Unbonded Contact Problem of a Plate on the Elastic Half Space" Jnl. Comp. Meth. Appl. Mech. Engng., 3, 105 - 113.

Svec, O.J. (1976) "Thick Plates on Elastic Foundations by Finite Elements" Jnl. Engng. Mech. Div., Proc. ASCE, 102 (EM3), 461 - 477.

Svec, O.J. and McNeicc, G.M. (1972) "Finite Element Analysis of Finite Sized Plates Bonded to an Elastic Half Space" Computer Methods in Applied Mechanics and Engineering, 1131, 265 - 277.

Wardle, L.J. and Fraser, R.A. (1974) "Finite Element Analysis of a Plate on a Layered Cross-Anisotropic Foundation" Proc. First. Int. Conf. Finite Element Methods in Engg., Uni of NSW, Australia, 565 - 578.

Wardle, L.J. and Fraser, R.A. (1975) "Methods for Raft Foundation Design Including Soil-Structure Interaction" Proc. Symp. Raft Foundations, Perth, Australia, 1-11.

Zhao, X.H. et al (1989) "Theory of Design of Piled Raft and Piled Box Foundations for Tall Building in Shanghai" (in Chinese), Tongji University Press, Shanghai, China.